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Predicting Adjustments in Shore and Offshore Sand Profiles on the Great Lakes

by

Edward B. Hands

COASTAL ENGINEERING TECHNICAL AID NO. 81-4

JANUARY 1981

U.S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER
Kingman Building
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This report summarizes a procedure for calculating the ultimate advance or retreat of the beach profile in response to a semipermanent change in water level elevation. The method, applicable to sandy shores throughout the Great Lakes, is illustrated by two examples. Hands (1980) describes the development of the procedure. A strictly empirical correlation useful for estimating shore retreat on a 1- to 5-year basis is discussed in Hands (1979). The present procedure couples field measurements with a model of how the profile ultimately reestablishes equilibrium with a new water level elevation. The former procedure would generally underestimate this longer term change.

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PREFACE

This report outlines a procedure for estimating the ultimate adjustment of the shoreline and of the offshore bathymetry to changes in mean water level on the Great Lakes. The procedure is based on a sediment balance model, calibrated and verified using profile changes measured on the eastern shore of Lake Michigan over a 9-year period. The procedure is generalized for application to other sections of the Great Lakes by considering regional variations in storminess, and by requiring local evaluation of relevant geomorphic and textural variables.

The report was prepared by Edward B. Hands, under the supervision of Dr. C.H. Everts, Chief, Engineering Geology Branch. Dr. W.L. Wood of Purdue University and J. Pope of the U.S. Army Engineer District, Buffalo, provided data used in the example problems. Appreciation is also extended to W. Birkemeier, C.H. Everts, R.J. Hallermeier, R.D. Hobson, R. Jachowski, and E. Meisburger for their review and suggestions which significantly improved this report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplementad by Public Law 172, 88th Congress, approved 7 November 1963.

Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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FIGURES

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

R_A sediment overfill factor--the ratio of sediment volume supplied by profile recession to that retained after sediment sorting, packing, and profile readjustment

sg (z) signum function having values of: 1 for $z > 0$; -1 for $z < 0$; and 0 for $z = 0$

X average horizontal exter of profile adjustment

x average horizontal displacement of the profile

Z average vertical extent of adjusting shore profile

z average change in elevation of the bottom profile or the water surface

PREDICTING ADJUSTMENTS IN SHORE AND OFFSHORE SAND PROFILES ON THE GREAT LAKES

by
Edward B. Hands

I. INTRODUCTION

This report briefly describes a method for predicting long-term changes in shoreline position and offshore bathymetry on the Great Lakes. Beach profiles fluctuate in response to storms and water level changes. On the Great Lakes both storms and water levels undergo prominent seasonal fluctuations. Superimposed on the seasonal fluctuations is a longer term variation in annual mean water level elevations. When measured over a number of years the net long-term change in water levels exceeds the range of seasonal fluctuations. The method described here for predicting long-term profile adjustments to changing lake levels is based on a conceptually sound, empirically verified model which includes allowances for regional variations in storm exposure, coastal geomorphology, and sediment texture.

II. THE IDEALIZED MODEL

As described by Bruun (1962), a rise in the mean elevation of the water surface tends to shift the equilibrium sand profile landward. As water levels rise, erosion prevails on the upper beach, and the shoreline retreats. Conceptually, the erosion supplies material to build the outer part of the responding profile upward. Eventually, the initial profile shape is reestablished farther inland and, at a distance above its initial position, equal to the change in water level, z, as depicted in Figure 1. If there are no longshore losses the ultimate retreat of the profile x can be calculated given the dimensions of the responding profiles, X and Z, and a measure of the stability of the shore-eroded material, R_A.

$$x = \frac{zX\left(R_A\right)^{sg\ z}}{Z}$$

where sg z = 1 if z > 0, and sg z = -1 if z < 0. Hands (1980) provides a more detailed description of the sequence of profile changes leading back to equilibrium and the derivation of the equation as a direct consequence of the conservation of sediment volumes. Also provided is an extended equation to cover the case of longshore imbalances in sediment transport. Though the concept behind the equation is straightforward, its evaluation in the field is problematic because the required dimensions of the responding profile (X and Z) will usually be unknown and depend on the local wave climate. Monitoring of beach and offshore changes in Lake Michigan has both verified the pertinence of the equation and simplified its evaluation for sandy shores throughout the Great Lakes.

III. EVALUATION OF TERMS IN THE EQUATION

1. Change in Water Level, z.

This is the given or independent variable; it refers to the change in mean elevation of the water surface which disturbed the equilibrium of the beach.

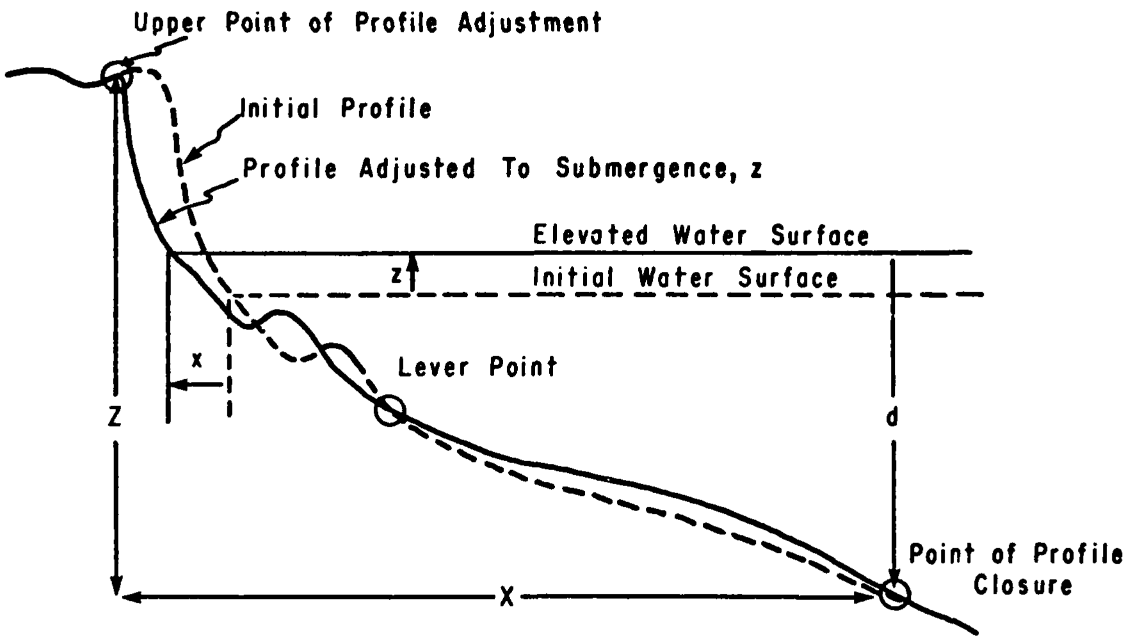

Figure 1. Sketch of profile measurements required to predict shore adjustment to a change in water level elevation. Providing there is no net gain or loss outside the control volume, constancy of profile shape requires that the ultimate shore retreat x be equal to zX/Z.

The change in water level elevation should persist at least long enough for equilibrium to be reestablished. The time required to do so will depend on the magnitude of the water level change and on the occurrence of storms which provide the energy necessary for reshaping the shore. To be consistent with the time frame in which other terms of the equation will be evaluated, the mean water level surface is expected to remain at its new elevation for more than 1 year. The new water surface elevation may refer to expected changes resulting from proposed modification to the lake control plans, or it may refer to a past change in lake level which could have resulted from natural variations in the water supply, but whose effect remains to be determined.

2. <u>Height of the Responding Profile, Z.</u>

This term refers to the vertical relief of the active beach which extends from the closure depth offshore to the top of the affected deposits on the backshore. The profile closure depth, beyond which the bottom does not respond to surface changes, depends on the local wave climate. Estimates of closure depths, based on the relationship between published wave climates and repetitive profiling on Lake Michigan (Hands, 1980), are tabulated in the Appendix for all five Great Lakes. The average height of the affected backshore deposits above the initial water surface should be determined from field measurements at the particular site of application. The sum of the closure depth (taken from the App.) and the average backshore height (determined from field surveys) is an estimate of Z.

3. Width of the Responding Profile, X.

The width of the responding profile refers to the horizontal distance between the landwardmost point of profile adjustment and the offshore closure depth. The width along many shore-normal profiles in the region of interest should be measured and averaged to obtain a representative value (Fig. 1).

4. Overfill Ratio, R_A.

The percent of eroded material by volume to be carried as suspended load beyond the closure depth should be estimated; additional erosion must compensate for the loss from the active profile. Hobson (1977) explains how to compute R_A, based on textural parameters of "native beach" and "borrow" materials. The same procedures can be applied here except that the parameters for the borrow materials must be based on a composite sample of the eroding section of shore; i.e., the upper beach, in the case of an increase in lake level, because this is the zone which supplies sediment to rebuild the profile (Fig. 1). If lake levels decline, then erosion below the lever point supplies material to prograde the upper part of the profile (Fig. 1). In this case, the lower profile (between lever and closure points) corresponds to the "borrow area." In either case "native" characteristics must be based on a composite sample of the entire responding profile, from the upper limit of profile adjustment to the point of profile closure. The lever point is useful in describing the sediment balance concept. In practice it is an ill-defined transition zone separating areas of predominant erosion and deposition. For long-term adjustments this transition may occur in the vicinity of the outer bar, but its exact location is not critical for the application of present procedures.

If adequate data for calculating R_A are not available and the lake level is rising, R_A can be assigned a value of 1, provided that (a) there is less silt and clay in the beach and backshore than there is offshore, and (b) the mean grain size across the beach and backshore is greater than the mean size offshore. A value of $R_A = 1$ indicates that all eroded material is expected to remain in the zone of profile adjustment; if only P percent remains, then $R_A = 100/P$.

IV. EXAMPLE PROBLEMS

The following problems are evaluated on the basis of limited available survey data. They provide examples of the basic steps in applying the proposed method of profile prediction. If these predictions were intended to support actual design or management decisions, a more careful evaluation of field conditions would be required.

* * * * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * * * * *

GIVEN: A contemplated change in the regulation plan controlling the water supply to Lake Ontario would raise the long-term surface elevation 0.3 meter.

FIND: The effect the higher stages would have at the eastern end of Lake Ontario.

ANALYSIS: The barrier beaches and high dunes which characterize this stretch of shore are of special ecological and scenic value. Situated downwind from the major storm paths across Lake Ontario these barrier beaches are exposed to the highest storm waves reported on the Great Lakes, but because of relatively low land development there are few protective structures along this reach of the shore. Sand extends lakeward across a series of longshore bars. There are no known rock outcrops, and there is a close balance between southward and northward longshore transport.

EVALUATION OF TERMS:

$z = 0.3$ meter	Proposed long-term increase in lake level.
7.6 meters	Average height of the eroding dunes above mean lake level (from field surveys).
13.4 meters	Profile closure depth (from the App.).
$Z = 21.0$ meters	Sum of the two values obtained above.
$X = 2,414$ meters	Average distance of the 13.4-meter depth contour from shore. The vertical datum should be the same as the reference level below which closure depth was measured in the previous step.
$R_A = 1$	All of the material eroded from the upper beach is expected to remain within the bounds of the responding profile.

$$x = \frac{zX\left(R_A\right)^{sg\ z}}{Z} = \frac{0.3(2,414)\ 1}{21} = 34 \text{ meters (evaluating the equation)}$$

It is estimated that the higher stages would shift the equilibrium shore profile an average of 34 meters inland and raise it 0.3 meter above its present elevation.

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * * *

GIVEN: Assume a new regulation plan is proposed to modify the inflow to Lake Michigan and Lake Huron via the St. Marys River. If adopted, this plan would lower the long-term mean surface elevation of Lake Michigan and Lake Huron by 0.3 meter.

FIND: The effect the lower water levels will have on shore erosion at Indiana Dunes National Seashore.

ANALYSIS: The dredged channel and navigation structures at Michigan City, updrift of the Indiana Dunes National Seashore, block some of the potential sediment input from the east. Westward longshore transport out of the dune area thus creates a sand deficit and contributes to a long-standing erosion problem in the park. As lake levels fall, the shoreline withdraws and the

beach widens. Assuming lake currents and waves are not altered, they will tend to reestablish the previous profile shape at a lower and more lakeward position. Longshore losses to the west continue to exceed the net supply from the east. However, offshore where the bottom slope is gradual, lowering of the water surface brings bottom sediments into a shallower hydraulic regime. This results in landward sediment transport which steepens the nearshore slope, builds dunes on the widened beach, and feeds the longshore currents leaving the dune area to the west. The cumulative effect of these adjustments can be estimated using the equation.

EVALUATION OF TERMS:

$z = -0.3$ meter	Given (negative indicates a reduction in water level).
2.9 meters	Estimated average height of dunes expected to form on the widened beach lakeward of the present foredune.
11.1 meters	Profile closure (mean of depths at adjacent sites 28 and 29 in App.).
$Z = 14.0$ meters	Sum of the two values obtained above.
$X = 3{,}030$ meters	Average distance of the 11.1-meter contour from shore, based on field surveys.
$R_A = 1$	Offshore sands are expected to move onshore, and the wind is not expected to carry sand inland past the present foredune.

$$x = \frac{zX\left(R_A\right)^{sg\ z}}{Z} = \frac{-0.3(3{,}030)\ 1^{-1}}{14} = -65 \text{ meters} \quad \text{(evaluating the equation)}$$

It is thus estimated that lowering the lake level 0.3 meter will effectively shift the *equilibrium* position 65 meters lakeward. As previously mentioned, a net loss of sand will still prevail due to the predominance of transport to the west. Therefore, the *actual shoreline* is not expected to advance 65 meters lakeward. A reasonable interpretation is that there will be a long-term gain of 65 meters of beach that otherwise would have been lost by erosion if the water level had not been lowered. Dividing 65 meters by the average past recession rate would provide an estimate of when the avoided erosion would otherwise have occurred.

If 15 percent of the offshore sediments were thought to be too fine to remain in the active shore zone, then the width of shore "saved" should be reduced to $(1 - 0.15) \times -65$ meters = -55 meters. Note that a liberal estimate of future dune heights would also make the predicted savings in beach width more conservative.

* *

V. LIMITATIONS

The prediction scheme proposed here is based on a physically sound principle; its application has been shown to produce results in remarkably good agreement with actual measurements along a 50-kilometer reach of Lake Michigan's eastern shore. The study area included a wide range of shore types though sand was always the predominant material, and the range of wave conditions within the study area was narrow relative to its potential range among other sites of application (Hands, 1980). The model's simplicity should promote its widespread application. However, this very simplicity when contrasted to the actual complexities of nearshore processes, should also underscore the need for careful consideration of each application. Two broad areas of concern are (a) the interpretation of the results, and (b) the evaluation of the input values used in the prediction equation.

1. Interpretation of Results.

Recall that the model attempts to evaluate only the profile change induced by the change in water level. Other factors resulting in shore modification may be found in the Shore Protection Manual (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). If the other factors are significant, the resulting net effect can be combined with the water level induced change (as in eq. 4 in Hands, 1980).

The key element in the proposed prediction scheme is the *assumption* that the profile will return to a specific shape after being disturbed by a change in water level. It is fundamental, therefore, that the reasonableness of this assumption be fully considered in each application. The proposed model does not apply, for example, to perched beaches, rocky shores, or beaches overlying nonerodible substrates that will be exposed during profile adjustment.

To clarify the development of the equation, the initial and final profile shape has been referred to as the *equilibrium profile*. However, the known profile used to evaluate Z and X need not be in strict equilibrium so long as it represents a relatively stable *shape* to which the profile evolves after perturbation. It is not necessary for the profile to be stable before perturbation; e.g., the shore in example problem 2 was continually eroding, both before and after the lake level disturbance.

Obviously, seasonal and storm features also affect the profile shape. This complicates testing the assumption of constant overall shape, but it should not significantly affect the results of applying the discussed model. Of course, if significant seasonal fluctuations are known, they can be included with the changes predicted by the equation to provide a more complete prediction.

2. Evaluation of Terms.

The actual values used to evaluate the equation must be based on an adequate number of representative measurements and samples taken along the entire reach of shore for which the prediction is desired. Having carefully made these determinations, the engineer must then rely on the accuracy of the closure depth values given in the Appendix. These published values are based on the assumption that the profile closure depth is proportional to storm wave heights at the site. The proportionality constant has been estimated using

hindcasted, deepwater storm wave data of Resio and Vincent (1976) and actual profile changes measured in Lake Michigan (Hands, 1980). If the engineer feels that the published values seem too deep for a particular site (or perhaps too shallow) but lacks sufficient evidence to justify making a different choice, it would be easy and worthwhile to determine what effect the suspected error would have on the predicted response and on the conclusions that the prediction would support.

An error in estimating closure will cause errors in both the numerator and denominator of the equation. In some cases, these two errors may reinforce each other; in other cases, they may compensate for one another, or they may even cancel and have no effect on the results or conclusions. Which situation exists can be determined readily if, as previously recommended, a number of shore-normal profiles have been obtained, and the following steps are taken.

First identify the point where the typical profile reaches the published closure depth, then the point where it reaches the alternately contemplated closure depth. Draw a line through these two points. If the line extends below the average height of the erodible backshore deposits, then overestimating closure depth will cause the equation to overpredict the response; underestimating closure will cause the equation to underpredict the response. If the line extends above the backshore deposits, overestimating closure will underpredict response and underestimating will overpredict response. These relationships will apply regardless of whether the response is a retreat or an advance of the shore. The possibilities are indicated in Figure 2. Intersection of the line with the crest of the backshore deposits means that the choice between the two closure depths will have no effect on the calculated outcome.

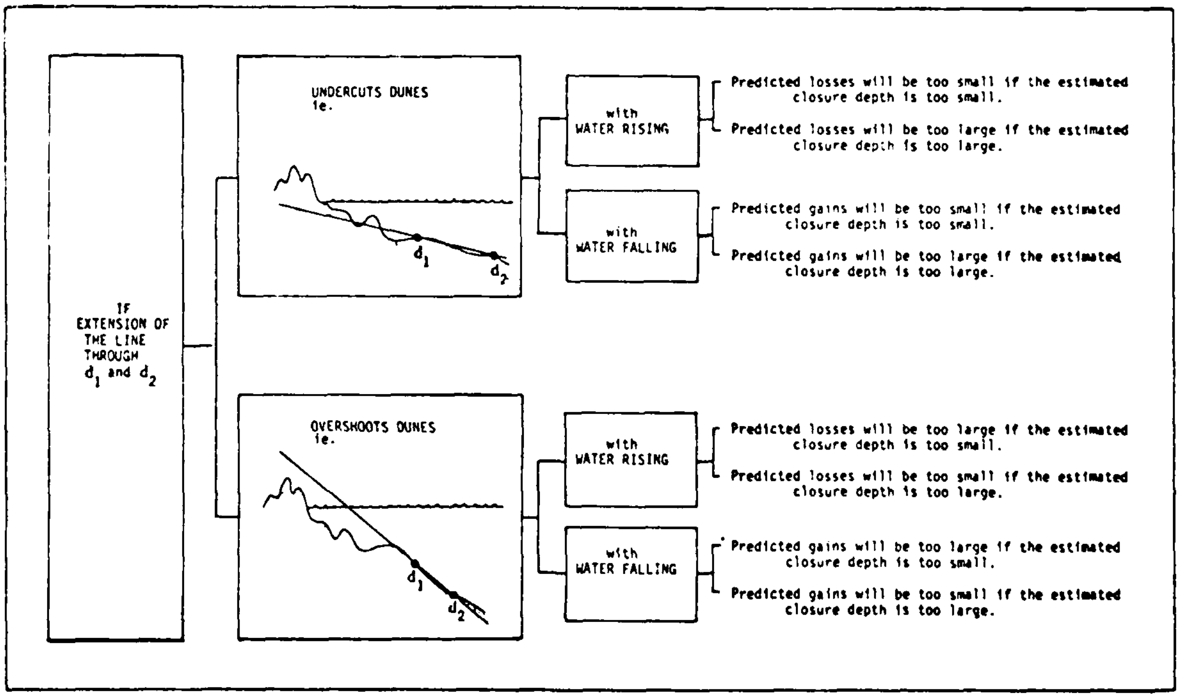

Figure 2. Diagram for determining if a suspected error would weaken or strengthen arguments based on the sediment balance prediction.

VI. CONCLUSION

A method has been presented for predicting one aspect to the long-term evolution of sandy shores. That aspect concerns displacement of the mean shore profile in response to long-term changes in water levels. This prediction method worked well in one hindcast instance involving a period of principally rising water (Hands, 1980). The degree of success found in future applications should be reported among Great Lakes engineers.

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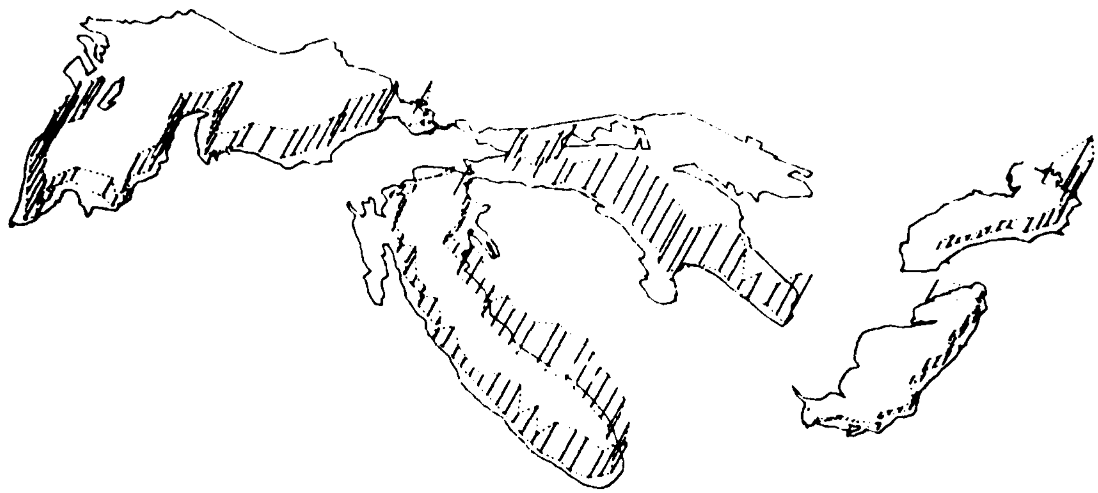
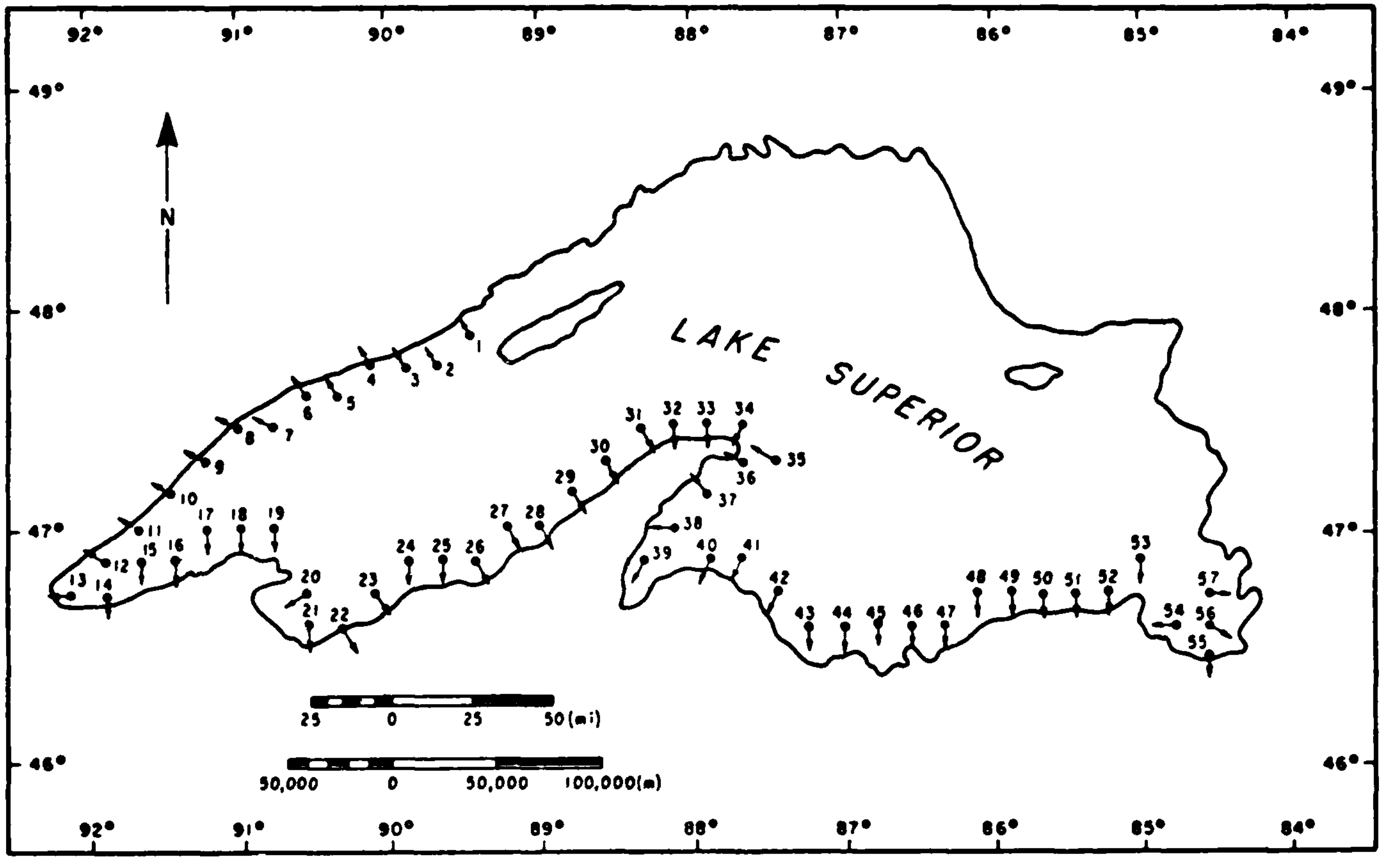
APPENDIX

ESTIMATED DEPTH OF PROFILE CLOSURE



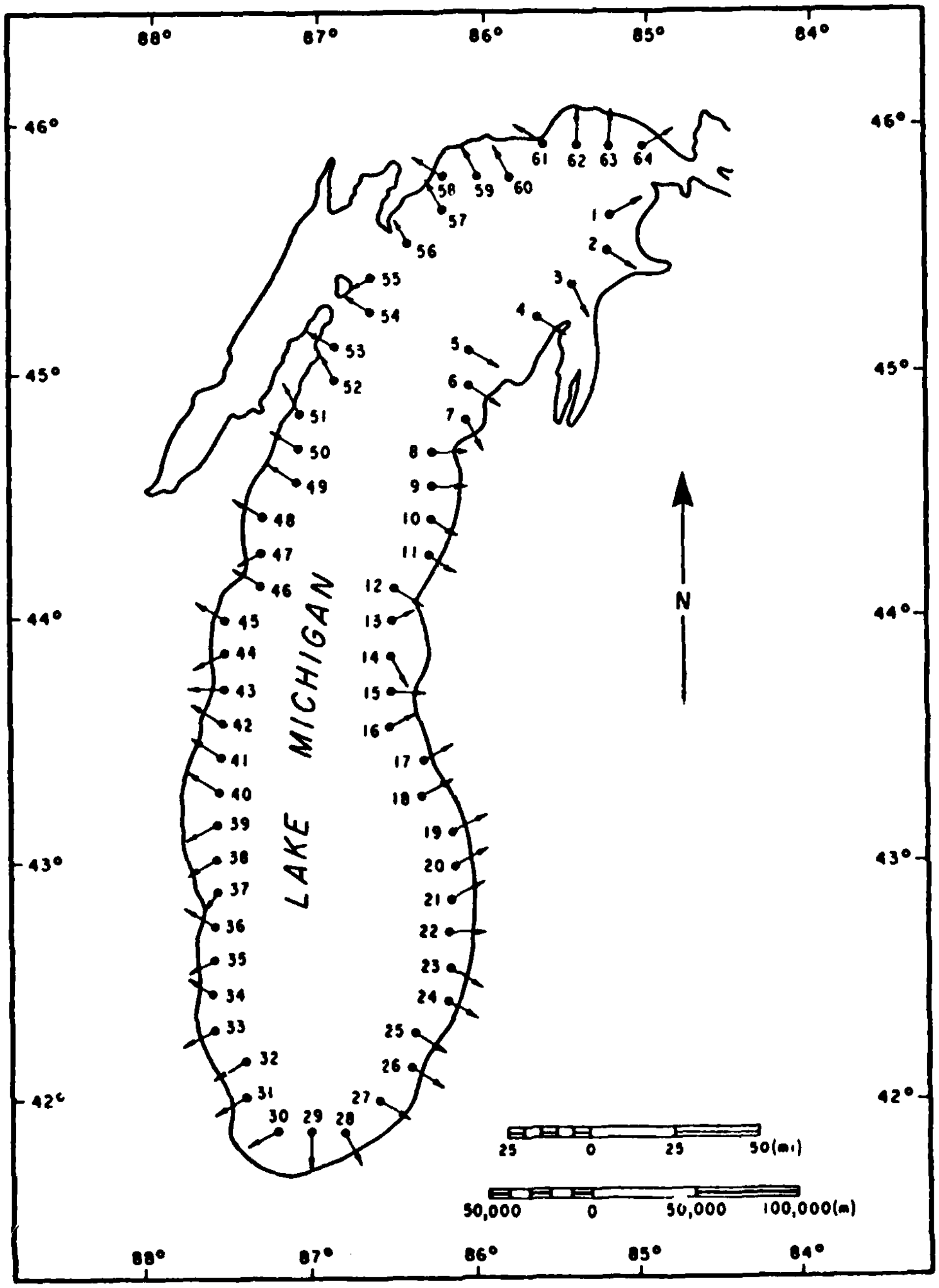
The height of the fence shown above is proportional to the inferred closure depths obtained by relating extreme deepwater wave statistics and the results of repetitive profiling on the eastern shore of Lake Michigan (Hands, 1980). Depths of profile closure beneath the stillwater surface are tabulated (in meters) on the following pages.



Study sites at Lake Superior.

Profile closure depths (in meters) at Lake Superior study sites.

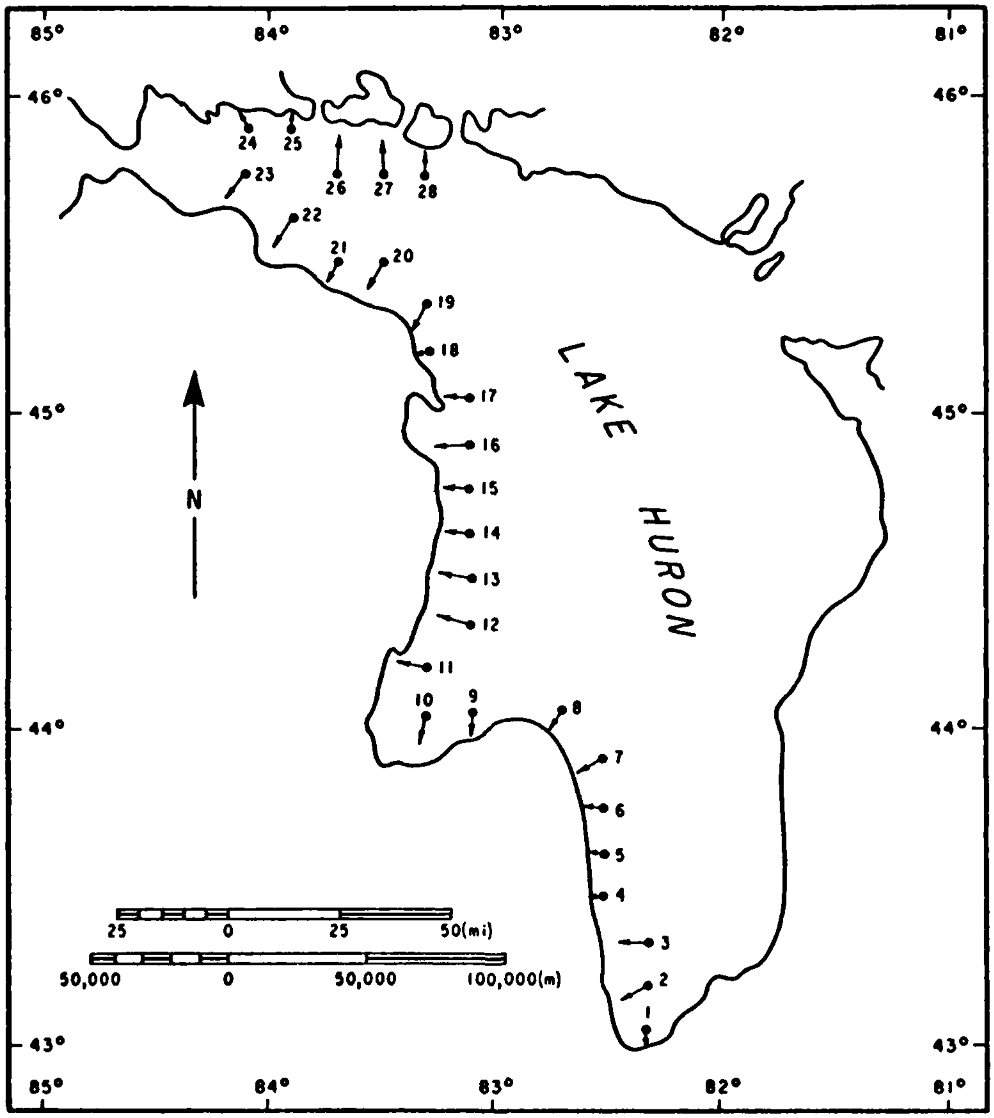
SITE	LOCATION	LATITUDE	LONGITUDE	CLOSURE DEPTH [M]
1	PIGEON BAY, MN	47.95	89.41	11.1
2	GRAND PORTAGE, MN	47.80	89.63	12.2
3	FARQUHAR KNOB, MN	47.80	89.83	12.2
4	BRULE RIVER, MN	47.80	90.08	12.4
5	GRAND MARAIS, MN	47.66	90.28	12.4
6	POPLAR RIVER, MN	47.66	90.49	12.4
7	CARLTON PEAK, MN	47.50	90.68	13.0
8	TACONITE HARBOR, MN	47.50	90.91	12.6
9	BAPTISM RIVER, MN	47.34	91.11	12.6
10	LITTLE TWO HARBORS, MN	47.20	91.32	12.6
11	AGATE BAY, MN	47.05	91.52	11.8
12	KNIFE RIVER, MN	46.90	91.72	11.6
13	DULUTH, MN	46.75	91.92	12.2
14	BRULE POINT, WI	46.75	91.72	9.2
15	IRON RIVER, WI	46.90	91.51	8.2
16	CRANBERRY RIVER, WI	46.91	91.30	8.8
17	SISKIWIT BAY, WI	47.06	91.09	8.0
18	POINT DETOUR, WI	47.07	90.88	8.4
19	ROCKY ISLAND, WI	47.08	90.67	8.6
20	MARBLE POINT, WI	46.78	90.45	9.7
21	SAXON HARBOR, WI	46.64	90.45	8.2
22	MONTREAL RIVER, MI	46.64	90.24	8.8
23	PRESQUE ISLE RIVER, MI	46.80	90.04	8.6
24	PORCUPINE MOUNTAINS, MI	46.94	89.81	10.3
25	PORCUPINE MOUNTAINS, MI	46.94	89.61	10.5
26	ONTONAGON, MI	46.94	89.40	11.1
27	FOURTEEN MILE POINT, MI	47.09	89.19	10.9
28	ELM RIVER, MI	47.11	88.98	11.3
29	REDRIGEE, MI	47.24	88.77	11.1
30	CALUMET, MI	47.38	88.55	11.1
31	EAGLE RIVER, MI	47.53	88.34	10.3
32	EAGLE HARBOR, MI	47.53	88.14	9.9
33	COPPER HARBOR, MI	47.53	87.91	9.5
34	SCHLATTER LAKE, MI	47.53	87.70	9.0
35	MONITOU ISLAND, MI	47.38	87.49	11.3
36	KEWEENAW POINT, MI	47.38	87.70	11.6
37	POINT ISABELLE, MI	47.24	87.91	11.3
38	TRAVERSE POINT, MI	47.09	88.14	11.6
39	PEQUAMING, MI	46.95	88.35	9.9
40	HURON RIVER POINT, MI	46.95	87.91	9.2
41	BIG BAY, MI	46.95	87.70	10.1
42	GARLIC POINT, MI	46.81	87.50	10.3
43	MARQUETTE, MI	46.66	87.29	10.7
44	DEERTON, MI	46.66	87.08	10.9
45	AU TRAIN BAY, MI	46.66	86.86	10.7
46	GRAND ISLAND, MI	46.66	86.65	11.1
47	GRAND PORTAL POINT, MI	46.65	86.45	11.3
48	AU SABLE POINT, MI	46.79	86.23	11.6
49	GRAND MARAIS, MI	46.78	86.02	11.6
50	SUCKER RIVER, MI	46.78	85.80	11.6
51	DEER PARK, MI	46.78	85.60	11.8
52	LITTLE LAKE HARBOR, MI	46.77	85.39	11.8
53	CRISP POINT, MI	46.91	85.18	11.1
54	PARADISE, MI	46.62	84.97	6.3
55	POINT IROQUOIS, MI	46.46	84.75	8.2
56	GROS CAP, MI	46.61	84.76	6.3
57	GOULAIS RIVER, MI	46.76	84.75	11.6



Study sites at Lake Michigan.

Profile closure depths (in meters) at Lake Michigan study sites.

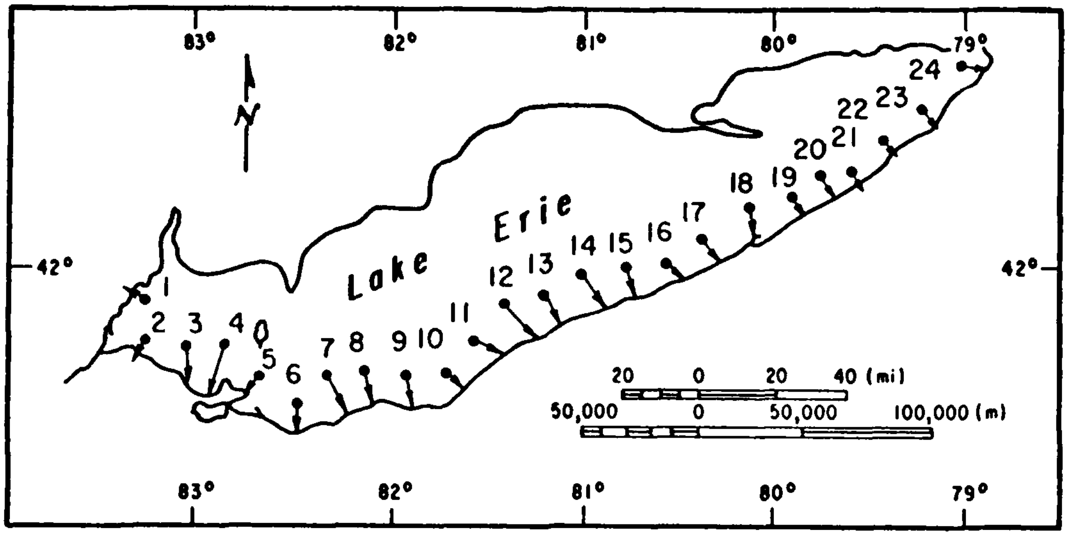
SITE	LOCATION	LATITUDE	LONGITUDE	CLOSURE DEPTH [M]
1	STURGEON BAY, MI	45.64	85.32	11.3
2	HARBOR SPRING, MI	45.50	85.32	7.8
3	FISHERMAN ISLAND, MI	45.37	85.50	9.0
4	TRAVERSE BAY, MI	45.23	85.72	8.6
5	TRAVERSE CITY, MI	45.10	86.15	7.8
6	MANITOU, MI	44.95	86.15	8.2
7	PLATTE LAKE, MI	44.80	86.17	9.7
8	FRANKFORT, MI	44.68	86.39	10.9
9	ARCADIA, MI	44.53	86.40	10.9
10	ONEKAMA, MI	44.38	86.40	9.0
11	MANISTEE, MI	44.24	86.41	9.5
12	BIG SABLE POINT, MI	44.09	86.63	9.0
13	LUDINGTON, MI	43.94	86.64	11.1
14	PENTWATER, MI	43.80	86.66	10.7
15	LITTLE SABLE POINT, MI	43.65	86.66	11.3
16	BENONA, MI	43.52	86.67	11.3
17	MONTAGUE, MI	43.36	86.48	12.0
18	MUSKEGON, MI	43.23	86.50	12.0
19	GRANDE HAVEN, MI	43.06	86.32	12.2
20	GRANDE RAPIDS, MI	42.93	86.33	11.8
21	HOLLAND, MI	42.78	86.33	11.1
22	DOUGLAS, MI	42.64	86.35	11.3
23	SOUTH HAVEN, MI	42.48	86.36	11.1
24	S SOUTH HAVEN, MI	42.34	86.37	10.9
25	BENTON HARBOR, MI	42.21	86.57	10.5
26	S ST. JOSEPH, MI	42.06	86.58	10.5
27	NEW BUFFALO, MI	41.93	86.78	10.1
28	MICHIGAN CITY, IND	41.78	86.99	10.9
29	BURNS HARBOR, IND	41.79	87.18	11.3
30	CHICAGO, ILL	41.80	87.38	10.7
31	CHICAGO SHIP CANAL, ILL	41.95	87.56	11.3
32	EVANSTON, ILL	42.10	87.56	11.1
33	HIGHLAND PARK, ILL	42.26	87.73	10.9
34	WAUKEGAN, ILL	42.40	87.73	8.0
35	KENOSHA, WI	42.54	87.73	10.9
36	S RACINE, WI	42.69	87.71	8.2
37	N RACINE, WI	42.83	87.70	10.9
38	S MILWAUKEE, WI	42.97	87.69	10.5
39	MILWAUKEE, WI	43.12	87.68	10.1
40	S PORT WASHINGTON, WI	43.27	87.68	8.2
41	PORT WASHINGTON, WI	43.41	87.67	7.8
42	N PORT WASHINGTON, WI	43.55	87.66	8.0
43	S SHEBOYGAN, WI	43.69	87.65	8.4
44	N SHEBOYGAN, WI	43.84	87.65	9.9
45	MANITOWOC, WI	43.98	87.64	8.0
46	TWO RIVERS, WI	44.13	87.43	7.8
47	RAWLEY POINT, WI	44.27	87.42	9.5
48	KEWAUNEE, WI	44.42	87.41	8.0
49	ALGOMA, WI	44.56	87.20	7.6
50	STURGEON BAY CANAL, WI	44.70	87.20	7.6
51	JACKSONPORT, WI	44.84	87.10	9.9
52	BAILEYS HARBOR, WI	44.98	86.98	9.5
53	N CANAL LIGHT, WI	45.14	86.96	7.6
54	WASHINGTON ISLAND, WI	45.27	86.74	7.1
55	FISHERMAN SHOAL, WI	45.41	86.73	6.7
56	ESCANABA, MI	45.54	86.52	9.9
57	POINT AUX BARQUES, MI	45.68	86.30	8.6
58	N POINT AUX BARQUES, MI	45.83	86.29	6.9
59	MANISTIQUE, MI	45.83	86.08	8.2
60	PORT ISLAND, MI	45.81	85.88	7.8
61	POINT PATTERSON, MI	45.94	85.66	5.5
62	MILLE COQUINS REEF, MI	45.94	85.45	4.6
63	SAULT STE MARIE, MI	45.93	85.25	5.8
64	BREWOORT LAKE, MI	45.92	85.04	7.8



Study sites at Lake Huron.

Profile closure depths (in meters) at Lake Huron study sites.

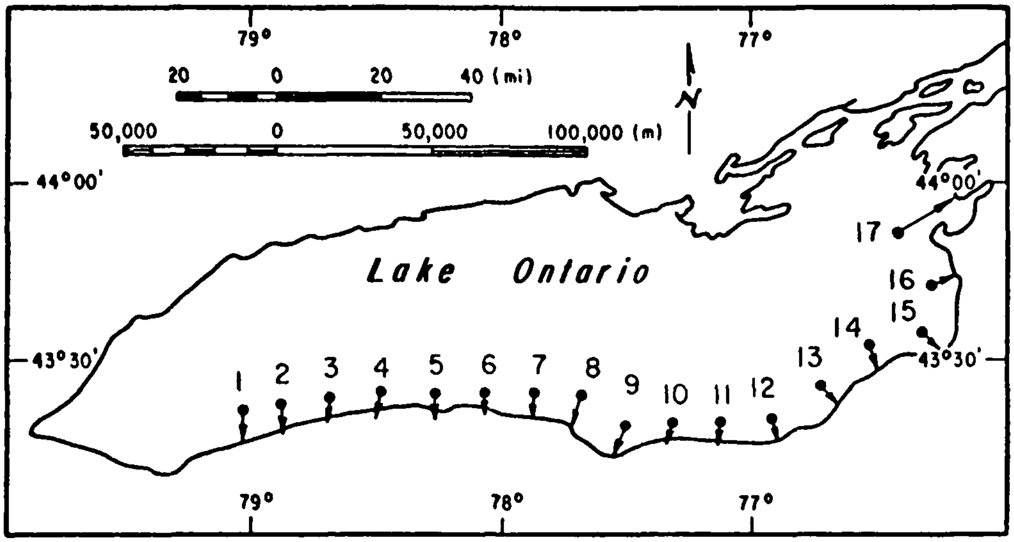
SITE	LOCATION	LATITUDE	LONGITUDE	CLOSURE DEPTH [M]
1	PORT HURON, MI	43.02	82.33	13.0
2	LAKEPORT, MI	43.16	82.33	12.2
3	LEXINGTON, MI	43.31	82.33	9.9
4	PORT SANILAC, MI	43.45	82.52	10.5
5	FORESTVILLE, MI	43.59	82.52	7.8
6	HELENA, MI	43.74	82.52	11.3
7	HARBOR BEACH, MI	43.88	82.52	12.0
8	HURON CITY, MI	44.03	82.71	12.2
9	PORT CRESCENT, MI	44.03	83.11	12.4
10	ENTRANCE SAGINAW BAY, MI	44.03	83.30	12.6
11	TAWAS CITY, MI	44.17	83.30	13.0
12	OSCODA AU SABLE, MI	44.31	83.11	12.4
13	GREENBUSH, MI	44.46	83.11	12.4
14	HARRISVILLE, MI	44.60	83.11	13.0
15	BLACK RIVER, MI	44.74	83.11	12.8
16	OSSINEKE, MI	44.89	83.11	12.8
17	NORTH POINT, MI	45.04	83.11	12.8
18	ROCKPORT, MI	45.18	83.30	12.6
19	STONE PORT, MI	45.32	83.30	10.9
20	ADAMS POINT, MI	45.46	83.50	9.7
21	ROGERS CITY, MI	45.46	83.70	10.5
22	HAMMOND BAY, MI	45.61	83.90	9.9
23	CORDWOOD POINT, MI	45.75	84.09	8.8
24	POINT DOLOMITE, MI	45.89	84.09	11.3
25	DETOUR REEF, MI	45.89	83.90	10.5
26	W END DRUMMOND ISLAND, MI	45.75	83.70	10.3
27	FALSE DETOUR CHANNEL, MI	45.75	83.50	11.3
28	COCKBURN ISLAND, MI	45.75	83.30	11.8



Study sites at Lake Erie.

Profile closure depths (in meters) at Lake Erie study sites.

SITE	LOCATION	LATITUDE	LONGITUDE	CLOSURE DEPTH [M]
1	MONROE, MI	41.87	83.27	6.7
2	CEDAR POINT, OH	41.72	83.27	6.5
3	LOCUST POINT, OH	41.70	83.07	6.1
4	PORT CLINTON, OH	41.69	82.90	6.3
5	LAKESIDE, OH	41.57	82.70	6.1
6	HURON, OH	41.42	82.50	7.4
7	VERMILION, OH	41.57	82.30	7.1
8	LORAIN, OH	41.57	82.12	6.7
9	AVON POINT, OH	41.56	81.93	7.1
10	CLEVELAND, OH	41.56	81.73	8.2
11	E OF CLEVELAND, OH.	41.68	81.53	7.8
12	FAIRPORT HARBOR, OH	41.88	81.35	7.8
13	E OF FAIRPORT HARBOR, OH	41.87	81.17	8.2
14	GENEVA, OH	42.00	80.98	8.4
15	ASHTABULA, OH	42.00	80.78	8.4
16	CONNEAUT, OH	42.00	80.60	8.6
17	GIRAD, PA	42.12	80.38	8.6
18	ERIE, PA	42.27	80.17	8.2
19	E OF ERIE, PA	42.27	79.98	8.4
20	E OF NORTH EAST, PA	42.41	79.75	8.4
21	WESTFIELD, NY	42.41	79.57	8.6
22	DUNKIRK, NY	42.55	79.35	7.1
23	ANGOLA, NY	42.68	79.15	7.8
24	BUFFALO, NY	42.83	79.94	10.1



Study sites at Lake Ontario.

Profile closure depths (in meters) at Lake Ontario study sites.

SITE	LOCATION	LATITUDE	LONGITUDE	CLOSURE DEPTH [M]
1	FORT NIAGARA, NY	43.43	79.03	8.0
2	WILSON, NY	43.43	78.83	8.6
3	APPLETON, NY	43.45	78.63	7.1
4	THIRTY MILE POINT, NY	43.45	78.46	7.1
5	LAKESIDE PARK, NY	43.45	78.25	7.6
6	KENDALL, NY	43.47	78.07	7.8
7	NORTH HAMLIN, NY	43.47	77.87	8.2
8	WEST ROCHESTER, NY	43.48	77.65	7.6
9	EAST ROCHESTER, NY	43.37	77.47	9.0
10	PULTNEYVILLE, NY.	43.37	77.25	9.2
11	SODUS, NY	43.38	77.07	9.5
12	WOLCOTT, NY	43.38	76.87	9.5
13	FAIRHAVEN, NY	43.48	76.68	12.2
14	OSWEGO, NY	43.63	76.50	11.8
15	LACINA, NY	43.63	76.28	12.2
16	BELLEVILLE, NY	43.77	76.28	13.4
17	GALLOO ISLAND, NY	43.91	76.50	10.1

Hands, Edward B.

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